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AAOmega spectroscopy of 29 351 stars in fields centered on ten Galactic globular clusters⋆

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ABSTRACT

Galactic globular clusters have been pivotal in our understanding of many astrophysical phenomena. Here we publish the extracted stellar parameters from a recent large spectroscopic survey of ten globular clusters. A brief review of the project is also presented. Stellar parameters have been extracted from individual stellar spectra using both a modified version of the Radial Velocity Experiment (RAVE) pipeline and a pipeline based on the parameter estimation method of RAVE. We publish here all parameters extracted from both pipelines. We calibrate the metallicity and convert this to [Fe/H] for each star and, furthermore, we compare the velocities and velocity dispersions of the Galactic stars in each field to the Besançon Galaxy model. We find that the model does not correspond well with the data, indicating that the model is probably of little use for comparisons with pencil beam survey data such as this.

Key words. (Galaxy:) globular clusters: individual: M4, M12, M22, M30, M53, M55, M68, NGC 288, NGC 6752, 47 Tuc - Galaxy: halo

1. Introduction

Globular clusters (GCs) are intriguing astronomical objects for many reasons. They are invariably found surrounding spiral and elliptical galaxies, have been used as tracers of galactic potentials (e.g. Kissler-Patig et al., 1999; Gebhardt & Thomas, 2009) and can be employed to test gravitational theories (e.g. Lane et al., 2009; Sollima & Nipoti, 2010). Despite decades of detailed examination, it is still uncertain how GCs formed (Bekki & Chiba, 2002; Lipscy & Plavchan, 2004; Mashchenko & Sills, 2005; Griffen et al., 2010; Lee et al., 2010) and their dark matter (DM) content is still debated, although they are usually considered to be DM-poor (Lane et al., 2009, and references therein). Recently, several studies revealed an interesting possible flattening in the velocity dispersions of several GCs at large radii, reminiscent of large elliptical galaxies, a signature of the kinematics of DM-dominated objects (Scarpa et al., 2007). These results called into question either the paucity of DM in GCs or our understanding of the nature of the gravitational interaction at low accelerations (below $a_0 \sim 10^{-10}\,\mathrm{ms}^{-2}$).

We performed detailed kinematic studies on ten Galactic GCs, with the goal of calculating independent velocity dispersion profiles to determine whether these results could be replicated (Lane et al., 2009, 2010a,b, hereafter Papers I, II and III respectively). In short, we found that the flattening of the velocity dispersion profiles shown in previous studies were not reproducible, despite two of our clusters being chosen to overlap with earlier investigations, namely M30 (Paper I) and NGC 288 (Paper III). Our results indicated that neither DM, nor a modification of gravitational theory, were required to reconcile the observed kinematics of our target GCs with current theory. In addition, we extended a recent metallicity calibration technique for open and globular clusters using the equivalent widths of the calcium triplet lines and the horizontal branch magnitude of the cluster (Cole et al., 2004; Warren & Cole, 2009), to the K band magnitude of the tip of the Red Giant Branch. This is several magnitudes brighter and can, therefore, be used for more distant clusters, and, more importantly, for GCs with hot, blue, horizontal branches whose stars do not exhibit strong calcium triplet lines (Section 2). Furthermore, a broad measure of the strength of the Galactic tidal field at various Galactocentric distances was made by comparing the velocity dispersions of the external and internal parts of the GCs. On the basis that the member stars at large radii are affected more by the external gravitational field, we showed that any flattening of the velocity dispersion profile could be attributed to this external field and did not require DM or modifications to gravity. We also argued that the lack of tidal heating signatures in our GCs at large Galactocentric radii is weakly suggestive of a spherical dark Halo (Paper III). In addition, we discovered the exciting possibility of a two-component kinematic population within 47 Tucanae, which we interpreted as evidence for the cluster forming as two individual clumps in the protocluster cloud which coalesced at a later date (with an upper limit of ∼ 7.3 ± 1.5 Gyr ago; Lane et al., 2010c). We also found an as yet unexplained anomalously rapid cooling of the outer regions of GCs following tidal heating by the Galactic disc.

⋆ The data described in Tables 1, 2 & 3 are only available in electronic form at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/530/A31`

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From these surveys we produced the largest sample to date of spectral data of both 47 Tucanae (47 Tuc) and M55 members, as well as large numbers of members of M4, M12, M22, M30, M53, M68, NGC 288 and NGC 6752. Although the main goal of this manuscript is to make these data public for further research, from these surveys we also obtained spectra from Galactic field stars in the foreground of the GCs, therefore, we also have a large sample of Galactic spectra at various latitudes and longitudes. In the current paper we compare the velocity dispersions of the Galactic stars at each location to current dynamical models of the Milky Way. Projects such as HERMES[1] (High Resolution Multi-object Echelle Spectrograph; Barden et al., 2008) on the Anglo-Australian Telescope show the importance of radial velocity/metallicity surveys over a large range of Galactic coordinates (particularly moving from the Disc to the Halo) for understanding Galactic evolution. Here we present our pencil beam survey as an analysis of the Galactic velocity dispersion as a precursor to surveys such as HERMES. Furthermore, a comparison is made between metallicities calculated using χ^2 analysis, as used by the Radial Velocity Experiment (RAVE; Zwitter et al., 2008), and the equivalent width method used by Lane et al. (2010a). Because our sample of stars from the 47 Tuc field is by far the largest, and also contains two GCs from the Small Magellanic Cloud (NGC 121 and Kron 3), we have used this field for most discussions and figures in the current paper.

2. Derived Parameters

All data was obtained on the AAOmega instrument on the Anglo-Australian Telescope (AAT), with the same gratings. We used the 1700D grating ($R = 10\,000$) on the red arm to observe the calcium triplet region (~ 8340Å–8840Å) and the 1500V grating ($R = 3700$) on the blue arm to include the swathe of iron and magnesium lines around ~ 5200Å. A detailed description of the observations, the membership selection process, and other details of the programme were given in Papers I, II and III.

Our data pipeline (see Kiss et al., 2007), which calculates various stellar parameters, is based on the RAVE pipeline. All data from this programme was reduced using both the RAVE pipeline (which has been modified for use with AAOmega data) and our own for comparison. These two pipelines work in slightly different, albeit similar, manners. The Kiss et al. (2007) pipeline uses an iterative process to obtain best fits to synthetic spectra from the library by Munari et al. (2005), which are degraded to the resolution of AAOmega, and this model is cross-correlated with the observed spectra to calculate the stellar parameters. The RAVE method obtains the best fit templates using penalised χ^2 rather than cross correlation (a detailed description of the template matching, and subsequent parameter estimation processes for each are given by Kiss et al., 2007; Zwitter et al., 2008). The Kiss et al. (2007) version of the pipeline also differs slightly from the modified RAVE pipeline in that it trilinearly interpolates the spectra in the synthetic library (refining the grid in $T_{\rm eff}$, $\log g$ and [m/H]). This leads to resolution of 50 K in $T_{\rm eff}$, 0.1 in $\log g$ and 0.1 in [m/H], whereas the RAVE version reduces to a nonlinear interpolation on the six dimensions of the parameter space. Furthermore, The Kiss et al. (2007) pipeline enforces one more iteration than the RAVE pipeline in the fitting process when calculating the radial velocities, which may provide a small improvment in the quality of the radial velocity estimate.

In most cases the RAVE extracted parameters are very similar to those from our own pipeline, however, there is a small but significant offset between the uncalibrated metallicity ([m/H]) extracted from the RAVE pipeline and those from ours (Figure 1). This is a known limitation of the RAVE pipeline which overestimates the metallicity for low metallicities due to the noise model assuming the same S/N for all pixels (Zwitter et al., 2008). Due to these subtle differences between the methods, and parameter estimates, we publish here all parameters from both pipelines. Published parameters are shown in Tables 1, 2 and 3; all data are available via the CDS.

2.1. Parameter Uncertainties

JHK magnitudes are taken directly from the 2 Micron All Sky Survey (2MASS), and, therefore, have an uncertainty of ~ 0.03 magnitudes (Skrutskie et al., 2006). V and I magnitudes are estimated from 2MASS JHK using unpublished transformations by G. Bakos (private communication). We have verified that these transformations have an uncertainty of V ~ 0.2 and I ~ 0.1 magnitudes by cross correlation with data by Weldrake et al. (2004), who provide VI photometry of 43 067 stars within ~ 30′ of 47 Tuc to better than 0.03 magnitudes.

Rotational velocity ($v_{\rm rot}$) estimates are theoretical because they come directly from the synthetic spectra by Munari et al. (2005), however, the lack of any inclination information means $v_{\rm rot}$ can be considered $v{\cdot}\sin(i)$. We do not derive a formal uncertainty on the quoted values of $v_{\rm rot}$, but because the two pipelines derive $v_{\rm rot}$ directly from the synthetic spectra, we can estimate an uncertainty by simple comparison between the two pipelines. The mean difference of $v_{\rm rot}$ between the two pipelines is ~ $12\,{\rm km\,s^{-1}}$. Taken at face value this can be considered the uncertainty on $v_{\rm rot}$, however, due to the spectral resolution of the observations we advise that values of $v_{\rm rot} \lesssim 30\,{\rm km\,s^{-1}}$ are much less reliable.

Similarly, because $T_{\rm eff}$ and $\log g$ are taken directly from the synthetic spectra for both pipelines, and because we do not derive any formal uncertainties for these parameters, the mean differences between the two pipelines (276.5 K and 0.6, respectively, see Figure 3) can be taken as the face value uncertainties.

At the resolution of our observations, and due to the density of the template spectra, microturbulence values of $\lesssim 2\,{\rm km\,s^{-1}}$ are not resolved. Therefore we recommend that this be taken as the minimum uncertainty on the microturbulence values, although the true uncertainties are likely to be larger.

The uncertainties in all metallicities ([m/H], [M/H] and [Fe/H]) are ±0.1 dex (see Section 3.2 and Figure 5).

Note that both [α/Fe] and microturbulence estimates are highly unreliable and should be treated with caution (see Zwitter et al., 2008, for additional details of parameter reliability and uncertainties for parameter estimates from the RAVE pipeline). Furthermore, the velocity uncertainties from the RAVE pipeline are the errors on the fits of the maxima of the correlation functions using a quadratic function. They are, therefore, not physical uncertainties on the radial velocities and tend to overerestimate the true uncertainties by about 20%. The radial velocity uncertainties from the Kiss pipeline are the formal errors from gaussian fits to the cross correlation function profiles. Again, these are not physical uncertainties and may also slightly overestimate the true uncertainties, however, the difference between the velocity estimates themselves from the different pipelines is small. Although the overall mean difference between the two pipelines for the 47 Tuc field is ~ $4.2\,{\rm km\,s^{-1}}$, this is mainly due to the large uncertainties in radial velocity estimates for the hot stars and reduces to ~ $0.3\,{\rm km\,s^{-1}}$ when comparing only those stars selected as members (see Figure 2); derived

[1] http://www.aao.gov.au/AAO/HERMES/

Table 1. Parameters published in the current paper from the RAVE pipeline for all fields. The final column designates whether the star was classified as a member in Papers I, II and III. See text for explanations of the parameters and associated uncertainties.

Cluster/Field
RA (radians)
dec (radians)
estimated I magnitude
field name
fibre number
V_r (km s^{-1})
V_r uncertainty (km s^{-1})
$T_{\rm eff}$ (K)
log g
[m/H]
[α/Fe]
microturbulence (km s^{-1})
rotational velocity (v·sin[i])
cluster member (yes/no)

Table 2. Parameters published in the current paper from the Kiss pipeline (with fields centered on M22, M30, M53 and M68). The final column designates whether the star was classified as a member in Papers I, II and III. See text for explanations of the parameters and associated uncertainties.

Cluster/Field
Star ID
V_r (km s^{-1})
V_r uncertainty (km s^{-1})
sum of the equivalent widths of the CaT lines (Å)
RA (degrees)
dec (degrees)
estimated V magnitude
$T_{\rm eff}$ (K)
log g
[m/H]
rotational velocity (v·sin[i])
distance from cluster centre (″)
position angle
cluster member (yes/no)

velocities for stars with $T_{\rm eff} \gtrsim 9000$ K are much less reliable as these have the CaT lines overtaken by strong P13, P15, and P16 hydrogen Paschen lines (e.g. Frémat et al., 1996).

The RAVE collaboration represents the state of the art in the extraction of many parameters from stellar spectra. The small deviations between the parameters extracted with the modified RAVE pipeline and those extracted using our own pipeline show that our software is also representative at this level (Figures 2 and 3).

3. Results

3.1. Kinematics of Galactic Field Stars

Despite the main focus of this paper being the publication of the data, we include some analysis of the field stars here. To do this, it was first necessary to exclude all stars considered members of the GCs (i.e. extract the field stars from the complete dataset). Our strict membership selection method in Papers I, II and III evidently did not extract all cluster members because it is obvious some have been left behind (Figure 4). It was, therefore, necessary to impose an additional cut based on the distance from the centre of the cluster to ensure we removed all cluster members before the model comparisons.

Table 3. Parameters published in the current paper from the Kiss pipeline (with fields centered on 47 Tuc, M12, M4, M55, NGC 288, NGC 6752). The final column designates whether the star was classified as a member in Papers I, II and III. See text for explanations of the parameters and associated uncertainties.

Cluster/Field
Star ID
V_r (km s^{-1})
V_r uncertainty (km s^{-1})
Sum of the equivalent widths of the CaT lines (Å)
RA (degrees)
dec (degrees)
estimated I magnitude
estimated V magnitude
$T_{\rm eff}$ (K)
log g
[m/H]
rotational velocity (v·sin[i])
J mag
H mag
K mag
distance from cluster centre (″)
position angle
cluster member (yes/no)

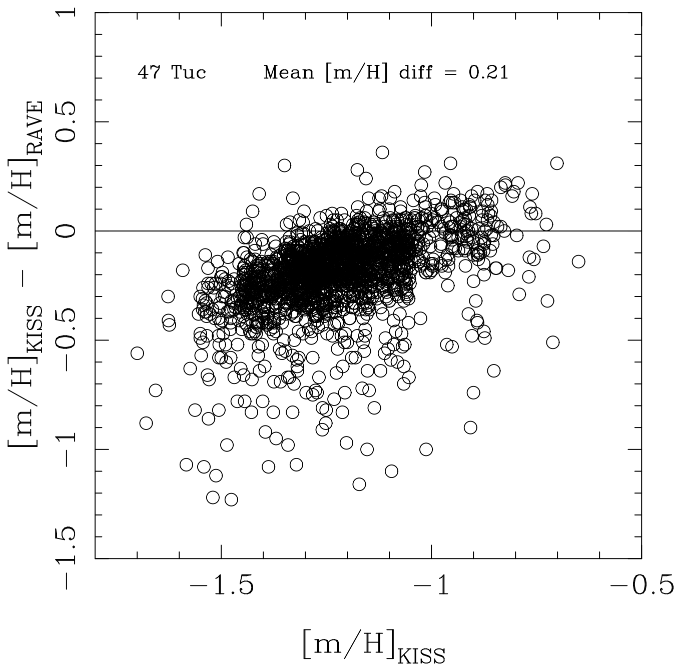

Fig. 1. Comparison of [m/H] from the RAVE pipeline versus that from our own for all stars in the 47 Tuc field. Notice the small offset between the parameter values.

Comparing our results with those of the best available dynamic Galaxy model (the Besançon model; Robin et al., 2003, see also `http://model.obs-besancon.fr/`) gives a measure of the accuracy of the model, which is known to have limitations (e.g. the Disc component truncates at 10 kpc, also see Figure 8 by Conn et al., 2008). Table 4 shows the velocity dispersion and mean velocities of all non-members from our ten fields and the Besançon model. The model fields have the same field centres

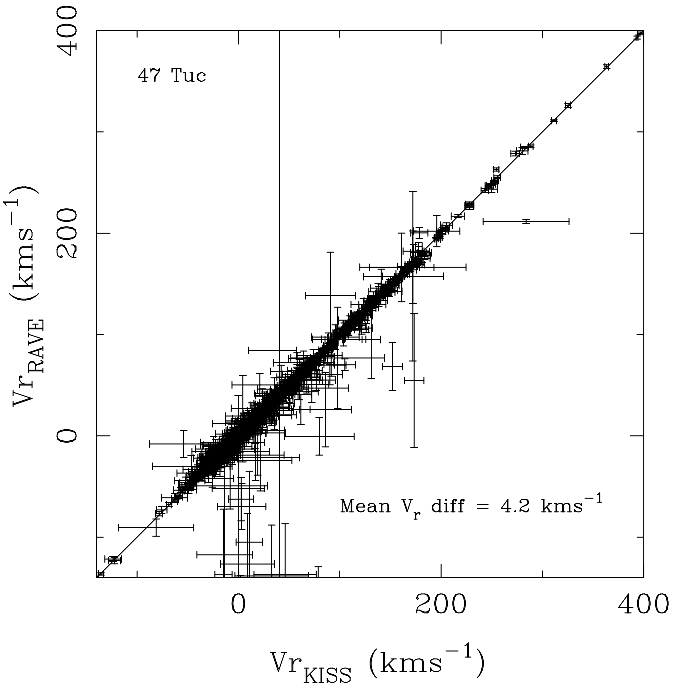

Fig. 2. Comparison of radial velocity estimates from the RAVE pipeline versus that from our own for all the stars in the 47 Tuc field. Comparing only those stars determined to be members, the mean difference reduces to $\sim 0.3\,\mathrm{km\,s^{-1}}$ (Paper II). This is due to hot stars having strong Paschen lines (see text).

as our data fields and were chosen to contain a similar number of stars, with the same temperature ranges as our data. The velocity dispersions for the data were calculated using the Markov Chain Monte Carlo method described in Paper III. The lack of agreement between the model and our data is apparent in Table 4, however, the Besançon model is regularly employed for comparison with observational surveys (e.g. Conn et al., 2005, 2007, 2008). The deviation of the model from the data in the current paper highlights the model's limitations for comparisons with *pencil beam* surveys. This should be taken into consideration when using this model for analysis. The Besançon model is, however, very effective when used for comparisons with *large area* surveys (e.g. Reylé et al., 2010).

A possible source of the model's discrepancies with small field surveys is that, while the model does include the warp and flare of the Disc, it does not include any known tidal streams, of which there are many (e.g. Belokurov et al., 2007). Furthermore, note an apparent kinematically distinct population of stars with $100 \lesssim V_\mathrm{r} \lesssim 200\,\mathrm{km\,s^{-1}}$ in the 47 Tuc field (Figure 4). The Small Magellanic Cloud is in this field (Paper II) which also has a recessional velocity of $100 \lesssim V_\mathrm{r} \lesssim 200\,\mathrm{km\,s^{-1}}$ (e.g. Storm et al., 2004; Evans & Howarth, 2008; De Propris et al., 2010). The model cannot be expected to replicate the mean velocity, or dispersion, of a field such as this.

3.2. Metallicity Calibration Based on [m/H], T_eff and $\log g$

The RAVE project calibrated [M/H] and [Fe/H] based on [m/H], [α/Fe] and $\log g$ (see Equations 19, 20 and 21 by Zwitter et al., 2008, who found that, using this method, the results for both [M/H] and [Fe/H] were within ~ 0.2 dex of reference metallicities). We have used this same method to calculate [M/H] and [Fe/H] for all stars in the current survey. Since our pipeline

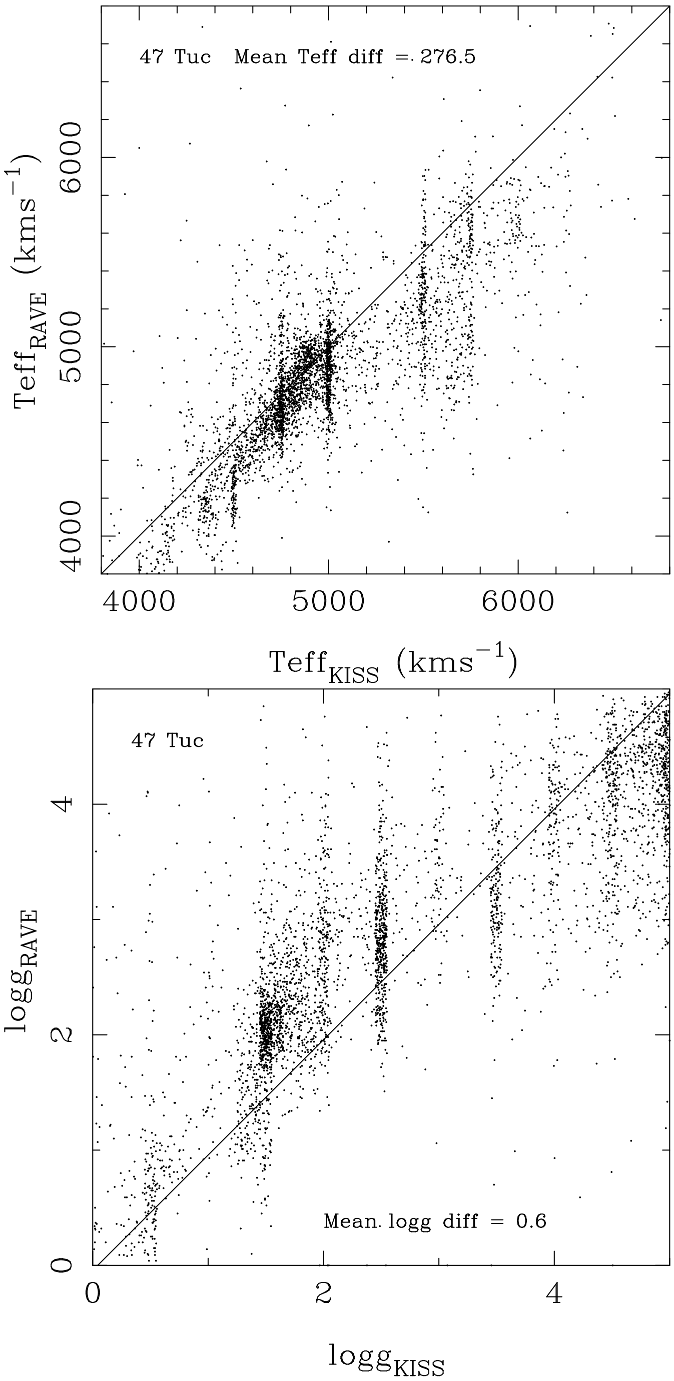

Fig. 3. Comparisons between the estimated T_eff and $\log g$ from each of the pipelines. Note that there is no obvious systematic offset between the two and that the average difference is small.

does not calculate [α/Fe] we cannot directly compare [Fe/H] calibrations based on our pipeline to those using the modified RAVE pipeline. However, [Fe/H] was calculated for the ten members of NGC 121 found in the 47 Tuc field in Paper II. These ten stars can also be seen in Figure 5 as the overdensity at [Fe/H]~ -1.6. In Paper II the metallicity for these stars were calculated using an equivalent width calibration method which found [Fe/H]$= -1.50 \pm 0.10$ for NGC 121, completely consistent with the overdensity in Figure 5. Furthermore, Figure 5 also shows the derived [Fe/H], using the RAVE methodology, for all stars from the M68 field. The overdensity centered on

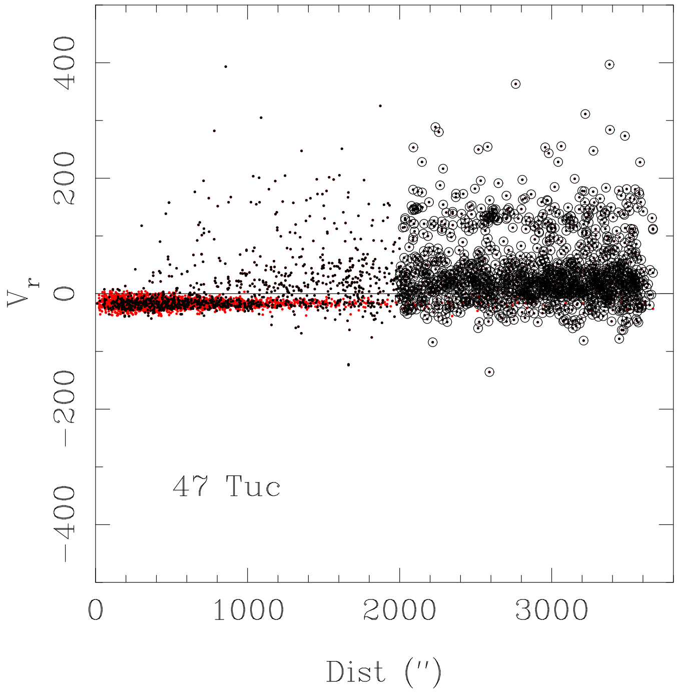

Fig. 4. Stars observed within in the 2dF field centered on 47 Tuc. Red points indicate those stars selected as members in Paper II and black points indicate those selected as non-members. Note the overdensity of black points within the velocity range of the cluster which are likely to be members. Circled black points indicate stars selected as non-members for the current paper.

Table 4. Comaprison between the velocity dispersion (σ) and systemic (mean) velocity of non-cluster member stars in each field and the Besançon model fields. All values are given in km s^{-1}.

Cluster/field	$\sigma_{\rm data}$	$\sigma_{\rm model}$	$V_{\rm sys(data)}$	$V_{\rm sys(model)}$
M4	61.7	78.2	-15.1	-36.2
M12	53.2	68.1	-20.4	0.9
M22	60.9	81.3	-2.8	32.6
M30	49.0	52.6	-10.9	-9.4
M53	53.0	40.0	0.1	-2.6
M55	59.4	74.6	-8.8	7.6
M68	35.9	51.4	7.2	12.8
NGC 288	40.8	38.1	7.8	6.1
NGC 6752	50.4	62.6	-5.5	-15.5
47 Tuc	58.8	49.8	39.1	16.0

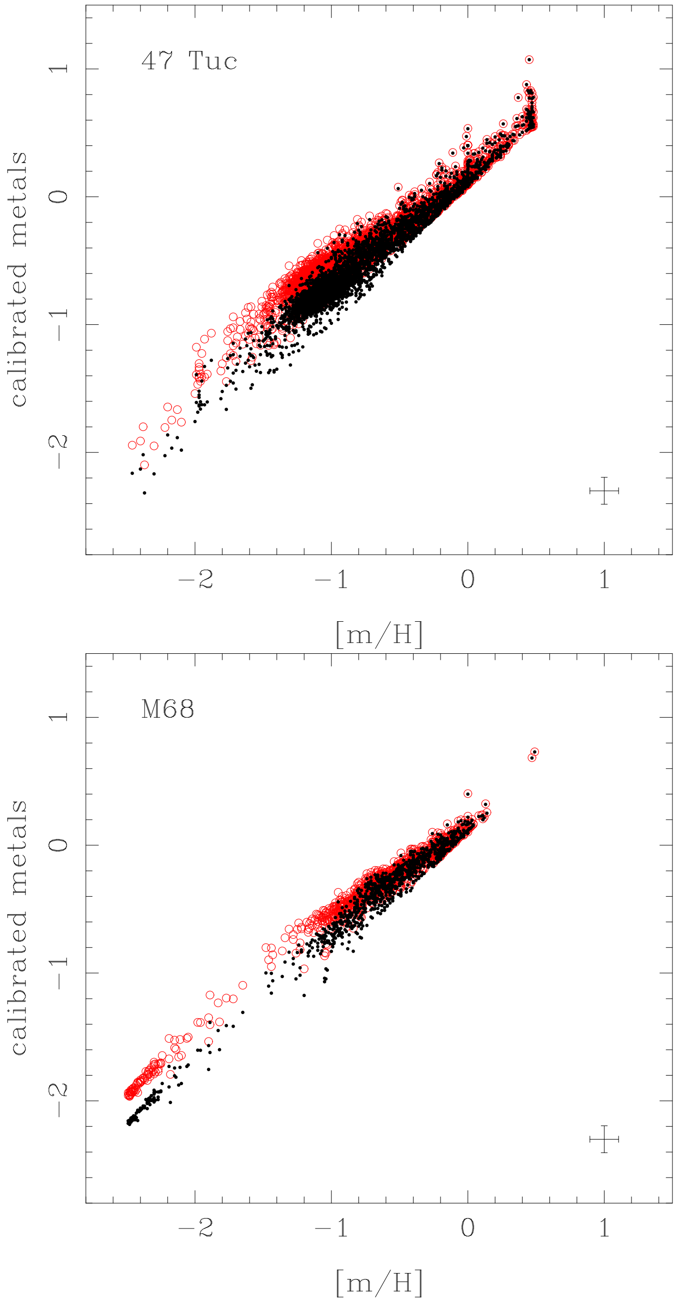

Fig. 5. The [Fe/H] and [M/H] calibrations for all stars in the 47 Tuc and M68 fields. These match well with the values of [Fe/H] calculated in Papers II & III via the equivalent widths of the CaII triplet lines and K magnitude of the Tip of the Red Giant Branch. The red circles represent [M/H] as the ordinate, and the black points represent [Fe/H] as the ordinate. A representative error bar is shown in the lower right of each panel.

[Fe/H]~ -2 are the stars determined to be members of M68 in Paper II, and are well separated in metallicity from the Galactic field stars. Using the equivalent width method, in Paper II we calculated [Fe/H]$= -2.06 \pm 0.15$ for M68, again consistent with that derived in this paper with the RAVE method. Zwitter et al. (2008) stated that it was not possible (or at least very difficult) to provide a physical explanation for the calibration relation between metallicities derived from equivalent widths or photometry methods to those obtained by χ^2 analysis. While this is still true, the current paper provides further evidence that the calibration relations by Zwitter et al. (2008) do, in fact, hold.

4. Conclusions

We present for publication the stellar parameters of 29 351 stars, observed with AAOmega in fields centered on ten Galactic globular clusters. Parameters were extracted using two pipelines, namely a version of the RAVE pipeline adapted to work with AAOmega data and a pipeline based on the RAVE methodology, and we publish here all parameters from both pipelines.

In addition, we find that the velocities, and velocity dispersions, of our Galactic field stars (those not belonging to the clusters) in each field do not agree well with those of the Besançon Galaxy model. This descrepancy may be due to the model lacking information on the many tidal features present in the Galactic halo, as well as nearby objects like the Magellanic Clouds. It is

apparent that there is a population which is kinematically distinct from the Galaxy in the 47 Tuc field (with $100 \lesssim V_\mathrm{r} \lesssim 200\,\mathrm{km\,s^{-1}}$). Since the SMC is in the background of this field, which has a radial velocity of $100 \lesssim V_\mathrm{r} \lesssim 200\,\mathrm{km\,s^{-1}}$, it is clear that we are seeing SMC stars in this field. We, therefore, suggest care is taken when using the Besançon model for comparison with pencil beam surveys.

Furthermore, we have calculated calibrated metallicities ([M/H] and [Fe/H]) for each star based on the RAVE method outlined by Zwitter et al. (2008) and these correspond well with [Fe/H] calculated via the equivalent widths of the calcium triplet lines originally published in Papers I, II and III.

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